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Polarization of X–ray emission from the Sgr B2 cloud

E. Churazov[1,2], R. Sunyaev[1,2], S. Sazonov[1,2]
[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, 85741 Garching, Germany*
[2] *Space Research Institute (IKI), Profsoyuznaya 84/32, Moscow 117810, Russia*

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ABSTRACT
The Sgr B2 giant molecular cloud is claimed to be an "X–ray reflection nebula" – the reprocessing site of a powerful flare of the Sgr A* source, occurred few hundred years ago. The shape of the X–ray spectrum and the strength of the iron fluorescent line support this hypothesis. We argue that the most clean test of the origin of X–rays from Sgr B2 would be a detection of polarized emission from this source.

Key words: Polarization – scattering – ISM: individual: Sgr B – Galaxy: centre – X-rays: general

1 INTRODUCTION

ASCA observations of the Sgr B2 giant molecular cloud revealed very hard X–ray spectrum with a very prominent iron fluorescent line at 6.4 keV (Koyama et al., 1996). This discovery provided an important confirmation of the hypothesis of Sunyaev, Markevitch and Pavlinsky (1993) that the diffuse emission from the giant molecular clouds in the Galactic Centre region is at least partly due to reprocessed emission of a powerful X–ray flare from the supermassive black hole Sgr A*. The geometry of the problem suggests that such flare could have happened few hundred years ago. The morphology and the spectrum of the reprocessed emission have been modeled by Sunyaev & Churazov 1998 and Murakami et al. 2000. Recent SAX (Sidoli et al., 2001) and Chandra data (Murakami, Koyama, Maeda 2001a) are broadly consistent with the assumption that reprocessed (reflected) emission is due to the past flare from Sgr A*. Main observational arguments in favor of this interpretation are:

- Remarkably hard shape of the Sgr B2 X–ray spectrum
- Extremely high flux in the neutral iron fluorescent line at 6.4 keV (equivalent width ∼1–2 keV).
- The side of the cloud towards Sgr A* is brighter in X–rays than the opposite side.

We argue below that the most convincing test of the origin of the diffuse X–ray emission from the Sgr B2 cloud would be a detection of polarized emission from this object. Recent progress in the development of the X–ray polarimeters for space missions (Costa et al., 2001) implies a drastic increase of the detector sensitivity and makes the Sgr B2 cloud a natural target for the polarimetric studies.

2 SIMULATIONS

We consider a uniform cloud with the radius of 10 pc and the Thomson optical depth of 0.5 exposed to the hard (power law photon index $\alpha = 1.8$) unpolarized X–ray radiation from an external source. As we argue below the particular values of the cloud size and its optical depth do not strongly affect the degree of the polarization of the reprocessed/reflected emission. The external source was assumed to be steady on the time scales comparable with the light crossing time of the cloud (the morphology of the reprocessed emission from the cloud illuminated by a short flare is considered in Sunyaev & Churazov 1998). The cloud consists of hydrogen (in molecular form), helium and admixture of heavy elements with the solar abundance. The reprocessed radiation was calculated via Monte–Carlo method. The following three processes have been taken into account: i) photoelectric absorption, ii) Compton scattering by bound electrons and iii) fluorescent emission of heavy elements. The cross sections for Compton scattering by electrons in hydrogen molecules and helium atoms were taken from Sunyaev & Churazov 1996, Vainshtein, Sunyaev & Churazov 1998 and Sunyaev, Uskov & Churazov 1999. The fluorescent yields and the energies of the fluorescent lines were taken from Kaastra & Mewe 1993.

In particular case of the Sgr B2 cloud (as a reflection nebula) and Sgr A* (as an external source) the projected distance of ∼100 pc is known. The cloud was assumed to be located at the same distance as Sgr A* and outgoing photons, used for calculating degree of polarization, were accumulated over small solid angle towards the observer's direction. The resulting spectrum and the degree of polarization are shown in Fig.1. For comparison the energy spectrum and the degree of polarization have been calculated for the case when scattering cloud is located at the same pro-

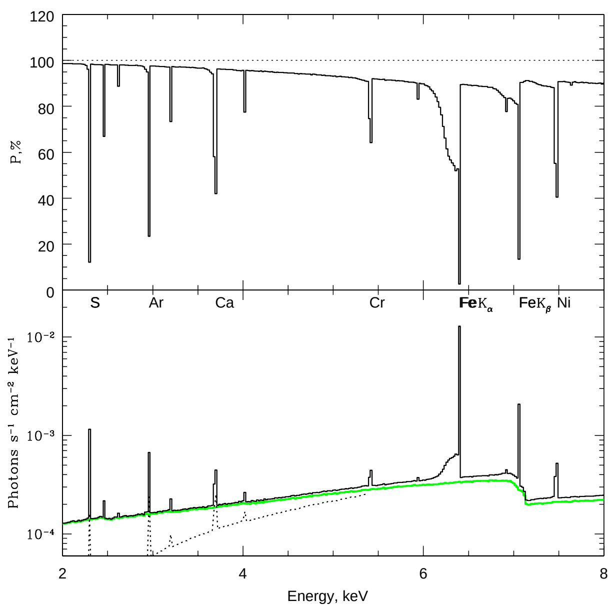

Figure 1. Bottom panel: A reflected energy spectrum (the solid line) of a spherical cloud exposed to hard X–ray emission from an external source. The cloud is assumed to be at the same distance from the observer as the primary source. The spectrum is shown with the energy resolution of 20 eV. The brightest fluorescent lines of the most abundant elements are marked. Note that for Ca, Cr and Ni the two components of the K_α lines (K_{α_1} and K_{α_2}) fell into adjacent energy bins causing the lines to look broader. The dotted line shows the suppression of the low energy part of the spectrum due to a photoabsorption over the line of sight for the hydrogen column density of 5 10^{22} cm^{-2}. The grey line shows the Stokes Q parameter, defined relative to the direction from Sgr A* to Sgr B2, as a function of energy (the U parameter is equal to zero). **Top panel:** Degree of polarization in the reflected spectrum. In the simulated geometry an average scattering angle of the primary radiation is close to 90°and the continuum radiation is almost completely polarized. The degree of continuum polarization slowly decreases with energy due to the increasing contribution from multiple scatterings. The fluorescent lines are produced in the cloud itself and are emitted isotropically. As a result degree of polarization drops strongly at the energies of the lines.

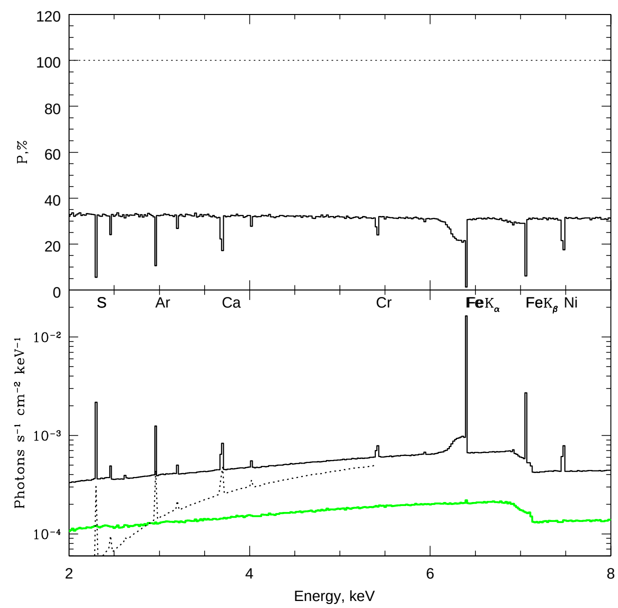

Figure 2. The same as in Fig.1, but for the scattering cloud located further 100 pc away from the observer than the illuminating source. Projected distance of the cloud from the source is 100 pc – the same as was assumed in Fig.1. An average scattering angle in this case is 135°and the degree of polarization is close to 33%. The same degree of polarization is expected for the cloud located by 100 pc closer to the observer than the illuminating source, when an average scattering angle in ∼45°.

jected distance, but further 100 pc away from the observer than the illuminating source (Fig.2).

3 DISCUSSION AND CONCLUSIONS

3.1 Energy spectrum

The spectra shown in Fig.1 and 2 have a typical "reflection" shape of the continuum and a set of strong fluorescent lines of the astrophysically abundant elements like S, Ar, Ca, Fe and Ni. At low energies (below ∼7 keV) the shape of the continuum emission is determined by the ratio of the scattering cross section to the photoabsorption cross section. Due to the coherent scattering by the electrons bound in hydrogen molecules and helium atoms the scattered continuum is higher (by a factor of 2 at lowest energies) than the reflected continuum calculated for free electrons. The "Compton shoulders" on the red side of the strong lines are smooth and do not show sharp features typical for scattering by the free cold electrons (Sunyaev and Churazov 1996). For the iron 6.4 keV line the flux in the shoulder is ∼10–20 % of the line flux.

Additional modification of the spectra shown in Fig.1 and 2 should be due to interstellar absorption along the line of sight. For the hydrogen column densities typical for the Galactic Centre region (i.e. N_H of ∼ 5 10^{22} cm^{-2}) the emission below 4-5 keV will be strongly suppressed.

3.2 Unpolarized radiation of the primary source

As is clear from Fig.1 the continuum emission is strongly polarized, while the emission in the fluorescent lines is not. This is of course a natural result given the geometry of the problem. For the neutral (or molecular) gas with solar abundance of heavy elements the first scattering gives the dominant contribution to the reflected continuum at energies below ∼7 keV. For a Thomson thick cloud the contribution from second scattering is attenuated by a factor $\delta(E) = \sigma_T/\sigma_{Ph}(E) \ll 1$, where σ_T is the Thomson cross section and $\sigma_{Ph}(E)$ is the photoelectric cross section at given energy E. For a cloud with a very small optical depth $\tau_T \ll 1$ the suppression factor for second scattering is $\delta(E) = \tau_T$. Therefore contribution of second scattering is almost always

modest (at least at low energies) and reasonable estimate of the degree of polarization can be made under single scattering approximation. The scattering cross section is proportional to the factor $(\mathbf{e_1} \cdot \mathbf{e_2})^2$, where $\mathbf{e_1}$ and $\mathbf{e_2}$ are the polarization vectors of the photon before and after the scattering. Since the angular size of the reflecting cloud (as seen from the illuminating source) is small then the degree of polarization P is related to the scattering angle θ via well known expression:

$$\mathrm{P} = \frac{1-\mu^2}{1+\mu^2}, \tag{1}$$

where $\mu = cos\theta$. In particular case of the scattering by $\sim 90^\circ$simulated above (Fig.1), the degree of polarization should be close to unity. The deviation of the degree of polarization from unity in simulations is caused mainly by the contribution of the second and subsequent scatterings to the total spectrum. For the second simulation (Fig.2) the scattering angle is around $135^\circ$and the degree of polarization is close to 33% in agreement with the expression (1) for Rayleigh law of scattering.

Using again the argument that the angular size of the cloud (as seen from the primary source) is relatively small one can treat the incident radiation as a narrow unpolarized beam and get simple estimate (see Appendix) of the degree of polarization for photons experienced two or more scatterings:

$$\mathrm{P_n} = \frac{1-\mu^2}{1+\mu^2+\frac{20}{15}(\left[\frac{10}{7}\right]^{\mathrm{n}-1}-1)}, \tag{2}$$

where n is the number of scatterings. From this equation it is clear that the degree of polarization rather slowly decreases with the increase of the number of scatterings. Therefore even although the degree of polarization decreases with energy (see Fig.1) due to increasing contribution from multiple scatterings, the reflected continuum radiation remains nevertheless strongly polarized at all energies. The direction of polarization remains the same (perpendicular to the direction from the primary source to the cloud) after any number of scatterings.

Fluorescent photons, which are born inside the cloud and are emitted isotropically should not be polarized as indeed seen in the simulations. The Compton shoulder of the fluorescent lines can be polarized for some specific geometries of the scattering clouds. E.g. for an optically thin, strongly elongated cloud (in the direction perpendicular to the line of sight) the shoulder can be strongly polarized. But in simple cases like considered here the shoulder can be polarized only weakly (compared to the continuum).

Thus sensitive polarimetric observations of the Sgr B2 cloud should reveal strongly polarized continuum and unpolarized fluorescent lines. The polarization direction must be perpendicular to the direction from the reflection nebula towards the primary source. Actual degree of polarization is a function of the scattering angle and therefore can be used to infer the mutual location of the Sgr B2 cloud and the Sgr A* source along the line of sight. For Sgr B2 cloud the total continuum flux in the 4-10 keV band is 1.5–2 10^{-4} $ph\ s^{-1}cm^{-2}$ as observed by ASCA. For a 4% efficient detector (see Costa et al., 2001) placed under $\sim 1000\ cm^2$ effective area mirror this source would yield about 6 10^{-3} $cnt\ s^{-1}$ in polarized flux. Therefore (assuming that the detector background can be neglected) a significant detection can be achieved in few 10^5 s. The Sgr B2 is not the only object which is suspected to be the "reflection nebula". Murakami et al., 2001b found strong fluorescent line emission from another rich molecular complex – Sgr C. As argued by Sunyaev, Markevitch, & Pavlinsky (1993) and Cramphorn & Sunyaev (2001) many other reflection sites could contribute to the diffuse emission in the Galactic Centre region and the Galactic Ridge. X–ray polarimetric studies would then allow one to reconstruct real 3-dimensional positions of the scattering clouds. Note however that (in the first scattering approximation) the degree of polarization is the same for the scattering angles of θ and $\pi - \theta$, which correspond to the cloud shifted with respect to the primary source towards or away from the observer by the same distance. In order to break this degeneracy one have to use detailed information on shape of the reflected continuum at low energies. For smaller scattering angles (the scattering cloud is closer to the observer than the primary source) the more distant side of the cloud is exposed to primary radiation and photoabsorption should suppress the reprocessed radiation at low energies.

3.3 Polarized radiation of the primary source

More confusing can be the case when the emission of the primary source is already polarized. For example this can be Sgr A* jet X–ray emission or emission from hot optically thin quasi-flat accretion disk (Sunyaev & Titarchuk, 1985). The incident light is assumed to consist of unpolarized component with the intensity $a0$ and the polarized component with the intensity a. The degree of polarization of the initial radiation is thus: $P_0 = a/(a + a0)$. The degree of polarization P of the scattered continuum radiation (in the one scattering approximation) can then be easily calculated:

$$\mathrm{P} = \frac{\sqrt{(1-\mu^2+\mathrm{P_0}(1+\mu^2)\mathrm{cos}2\phi)^2+4\mathrm{P_0^2}\mu^2\mathrm{sin}^2 2\phi}}{1+\mu^2+\mathrm{P_0}(1-\mu^2)\mathrm{cos}2\phi}, \tag{3}$$

where ϕ is the angle between the direction of polarization of the primary radiation and the perpendicular to the scattering plane. This would make the determination of the cloud position with respect to the primary source more complicated. However the continuum radiation will remain polarized in majority of cases and therefore the hypothesis of the Sgr B2 as the "reflection nebula" can still be tested with the polarimetric observations. Polarization of the incident radiation will also affect shape of the continuum spectrum because it will modify the contributions of single and multiple scattered photons to the total spectra. The equivalent width of the fluorescent lines will also change. E.g. consider the single scattering approximation for the 90°scattering. For the completely polarized primary radiation the scattered continuum will be attenuated by a factor $cos^2\phi$, while the intensity of the fluorescent line will not be affected. Thus the equivalent width of the line is:

$$EW(\phi) = \frac{EW_0}{2cos^2\phi}, \tag{4}$$

where EW_0 is the equivalent width of the line in the case of unpolarized primary radiation. Therefore when the direction of the primary radiation polarization is in the scattering plane the contribution from the first scattering to the continuum spectrum is zero and the equivalent width of the

iron line will be much larger than for unpolarized primary radiation. In reality presence of unpolarized component in the primary radiation and contribution from multiple scatterings will limit the maximal value of the equivalent width.

Finally we note that if the X–ray flare from the Sgr A* source was short compared to the light crossing time of the Sgr B2 cloud (see Sunyaev & Churazov 1998) then the time delay for photons undergoing two or more scatterings has to be taken into account when calculating the energy spectrum and the degree of polarization. In the first scattering approximation the results are unchanged: the continuum is polarized in accordance with the scattering angle and the flux in the fluorescent lines is completely unpolarized.

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APPENDIX A: POLARIZATION OF A NARROW BEAM AFTER SEVERAL SCATTERINGS.

Consider the narrow beam of unpolarized light in the scattering medium with the Rayligh scattering phase function. The light after n scattering can be represented as a two component vector:

$$\begin{pmatrix} I_{n,\parallel}(\mu) \\ I_{n,\perp}(\mu) \end{pmatrix}, \tag{A1}$$

where μ is the cosine of the angle with respect to the beam axis and $I_{n,\perp}(\mu)$ and $I_{n,\parallel}(\mu)$ are the intensities of light with the directions of polarization perpendicular and parallel to the plane formed by the initial beam and the direction of the photon. From the symmetry of the problem it is clear that only two components are needed to fully describe the polarization. The change of the polarization after additional one scattering is then governed by the simple transformation (e.g. Chandrasekhar, 1950):

$$\begin{pmatrix} I_{n+1,\parallel}(\mu) \\ I_{n+1,\perp}(\mu) \end{pmatrix} = \frac{3}{8} \times \tag{A2}$$

$$\int_{-1}^{+1} \begin{pmatrix} 2(1-\mu^2)(1-\mu'^2)+\mu^2\mu'^2 & \mu^2 \\ \mu'^2 & 1 \end{pmatrix} \begin{pmatrix} I_{n,\parallel}(\mu') \\ I_{n,\perp}(\mu') \end{pmatrix} d\mu'$$

The initial values of I for a narrow beam of unpolarized light are obviousely:

$$\begin{pmatrix} I_{0,\parallel}(\mu) \\ I_{0,\perp}(\mu) \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \delta(\mu-1) \\ \delta(\mu-1) \end{pmatrix}, \tag{A3}$$

where δ is a Dirac function. From (A2) it is clear that after any number of scatterings the intensities I can be written in the form:

$$\begin{pmatrix} I_{n,\parallel}(\mu) \\ I_{n,\perp}(\mu) \end{pmatrix} = \begin{pmatrix} a_n + b_n\mu^2 \\ c_n \end{pmatrix}. \tag{A4}$$

E.g. for the radiation scattered once we obtain, by substituting (A3) into (A2): $I_{1,\parallel} = 3/8\mu^2$, $I_{1,\perp} = 3/8$. I.e. $a_1 = 0$; $b_1 = 3/8$; $c_1 = 3/8$.

Inserting the expression (A4) into (A2) one gets the recursive relation for a_n, b_n and c_n:

$$\begin{pmatrix} a_{n+1} \\ b_{n+1} \\ c_{n+1} \end{pmatrix} = \begin{pmatrix} a_n + \frac{1}{5}b_n \\ -\frac{3}{4}a_n - \frac{1}{20}b_n + \frac{3}{4}c_n \\ \frac{1}{4}a_n + \frac{3}{20}b_n + \frac{3}{4}c_n \end{pmatrix}. \tag{A5}$$

From (A5) it follows that $c_{n+1} = a_{n+1}+b_{n+1}$. The remaining two relations are then simplify to:

$$\begin{pmatrix} a_{n+1} \\ b_{n+1} \end{pmatrix} = \begin{pmatrix} a_n + \frac{1}{5}b_n \\ \frac{7}{10}b_n \end{pmatrix}. \tag{A6}$$

Using (A6) and known values of a_1 and b_1 we obtain the explicit expression:

$$\begin{pmatrix} a_n \\ b_n \\ c_n \end{pmatrix} = \begin{pmatrix} \frac{1}{4} - \frac{1}{4}\left(\frac{7}{10}\right)^{n-1} \\ \frac{3}{8}\left(\frac{7}{10}\right)^{n-1} \\ \frac{1}{4} + \frac{1}{8}\left(\frac{7}{10}\right)^{n-1} \end{pmatrix}. \tag{A7}$$

Finally by substituting (A7) into (A4) we can calculate the degree of polarization of photons experienced n scatterings:

$$\mathrm{P_n} = \frac{\mathrm{I_{n,\perp} - I_{n,\parallel}}}{\mathrm{I_{n,\perp} + I_{n,\parallel}}} = \frac{1-\mu^2}{1+\mu^2+\frac{20}{15}(\left[\frac{10}{7}\right]^{\mathrm{n}-1}-1)}, \tag{A8}$$